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16. ABSTRACT

This research developed and field-tested a USV-based bathymetric survey platform with over five hours of operation and a top speed of 2.1m/s, while also upgrading Caltrans crewed boats with survey capability. Successful surveys were conducted using the USV, an inflatable boat, and a dive boat. The Norbit MBES ' s adjustable field-of-view was crucial for capturing data near bridge piers. An integrated obstacle avoidance system, using multiple proximity sensors, allowed automatic halting in autonomous modes. Recommendations include adding stereo cameras with ML to address LiDAR blind spots, integrating side-scan or 360° sonar for improved detection, and using MBES data in shallow water. Enhancements such as reinforcement learning for adaptive avoidance, battery optimization for weight reduction, higher-efficiency propellers, a rugged transport cart, thermal monitoring, and propulsion redundancy are suggested to improve reliability and mission endurance.

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Advanced Highway Maintenance and Construction Technology Research Center

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Evaluation of Uncrewed Surface Vessel-Based Topographic and Bathymetric Survey System in Flood Conditions

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Report Number: CA25-3926
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California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Problem, Need, and Purpose of Research

The California Department of Transportation (Caltrans) conducts topographical and bathymetric surveys for modeling channel water flow and early detection of bridge scour. These surveys are crucial for monitoring the health of substructural support elements. There are challenges to such operations for both deep and shallow water surveys. The challenges in shallow waters are related to fast flowing currents, submerged and unobservable debris, blockades, sensitive habitats, and the potential of the equipment (boat, crew, sensors). Caltrans needs a reliable teleoperated system benefiting from semi-automation or automation technologies for topographical and bathymetric surveys that remove safety concerns and make scheduling and undertaking of such operations easier.

Overview of Work and Methodology

Researchers at the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center developed the requirements for uncrewed surface vessels (USVs) that can be used for bathymetry operations under flood conditions and the limitations and potentials of incorporating automation options. We evaluated a small USV-based bathymetric survey system. A commercial-off-the-shelf (COTS) USV was procured and integrated into a COTS multi-beam echo sounder (MBES) system. Then, pilot bathymetric survey projects were conducted using the developed USV system near bridges. The latter aspect of this research was conducted in close connection with Caltrans staff involved in survey operations.

Major Results and Recommendations

This research successfully developed and field-tested a USV bathymetric survey platform, achieving over five hours of operational time and a top speed of 2.1 m/s (6.9 ft/s), while also enhancing Caltrans crewed boats with bathymetric survey capability. The project demonstrated successful bathymetric surveys using USV, an inflatable crewed boat, and a dive boat. The Norbit MBES software-configurable field-of-view (FOV) feature on the USV proved essential for gathering data from bridge piers up to the water surface and is a valuable addition to bathymetric survey systems.

An under- and above-water obstacle avoidance system was developed by integrating multiple proximity sensors and algorithms into the USV. The obstacle avoidance system enables the USV to halt automatically in auto, guided, or acro mode upon detecting obstacles, requiring operator intervention in complex scenarios.

Recommendations include integrating stereo cameras with machine learning (ML) algorithms to address LiDAR blind spots, incorporating side-scan or 360-degree sonar to improve underwater obstacle detection, and leveraging MBES sensor data for operations in shallow waters as low as one foot. Additionally, integrating reinforcement learning (RL) agents could enable more adaptive obstacle avoidance with minimal disruption to data collection.

To improve efficiency, weight reduction strategies, such as optimizing battery configurations to balance mobility and operational time, should be explored. The T500 thruster propeller blade design, currently optimized for low-speed thrust, could be modified to increase top speed and efficiency without adding additional thrusters. The USV transportation cart should also be improved to traverse rough and steep terrain more effectively. Addressing thruster motor controller overheating issues, which caused system resets and steering loss, is critical; incorporating a remote reset function via the USV controller and installing a temperature monitoring system for onboard electronics can mitigate this risk. Lastly, propulsion redundancy should be considered by adding backup motors, rudders, or steerable mounts, ensuring continued operation even in the presence of debris-induced failures, ultimately enhancing the USV's reliability for extended survey missions.

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Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
CAD	Computer aided design
CAN	Controller Area Network
CDEC	California Data Exchange Center
CFS	Cubic Feet per Second
COTS	Commercial Off the Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
ESC	Electronic speed controllers
FLS	Forward-Looking Sonar
FOC	Field Oriented Camera
FOV	Field of View
FPV	First Person View
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LiDAR	Light Detecting and Ranging

Acronym	**Definition**
LiPo	Lithium Polymer Battery
LOS	Line of Sight
MBES	Multi-Beam Echo Sounder
MHz	Megahertz
ML	Machine Learning
KGs	Kilograms
RC	Remote Control
RL	Reinforcement Learning
RTL	Return to Launch
SBC	Single Board Computer
SMI	Structure Maintenance Investigations
USB	Universal Serial Bus
USV	Uncrewed Surface Vessel

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Chapter 1:

Requirements for an Uncrewed Surface Vessel-based Bathymetry system in flood conditions

Overview

This task developed the requirements for a bathymetric unmanned surface vessel (USV) operation for the California Department of Transportation's (Caltrans) Structure Maintenance Investigation (SMI). The requirements included power, USV body control, remote control, telemetry, software, and hardware with the main objective of safe and stable operation of the USV and reliable bathymetry survey.

A bathymetric USV is composed of several key components that enable efficient surveying operations. These include:

- **Multibeam echo sounder (MBES):** Primary survey sensor for bathymetric mapping.
- **Control systems and sensors:** Essential for autonomous or remote guidance, and obstacle detection systems.
- **Propulsion and power systems:** Ensure stable and reliable movement during survey missions, often consisting of electric or fuel-based propulsion.
- **Hull design:** Houses all components while minimizing drag and optimizing hydrodynamic performance for stability and efficiency.

The development of the USV began with selecting an MBES that met the specific requirements of the Caltrans SMI operation. Once the MBES was chosen, an appropriate hull was selected based on a literature review of past systems, ensuring compatibility with the mounting requirements of the MBES. Following this, suitable control and electronic systems were integrated, including GPS for navigation, a ground station for communication, and a flight controller for autonomous operation. Each component was carefully chosen to optimize performance, reliability, and compatibility within the USV framework.

Mission Requirements

The primary objective of the USV platform discussed in this study is to conduct bathymetric surveys in diverse environments, including under flood conditions.

This capability is particularly crucial in areas near bridges where strong currents and limited access necessitate frequent surveys, posing significant operational challenges. To meet its mission objectives, the USV must satisfy several key performance requirements:

- **Strong current navigation**: The vessel must be capable of operating effectively in high-flow conditions, ensuring stability and maneuverability against strong currents.
- **Operational endurance**: The system must support continuous operation for at least two hours, providing sufficient battery capacity for uninterrupted data collection in a single deployment.
- **Payload capacity and size**: Given the onboard instrumentation, including a MBES, computational resources, and power systems, the USV must accommodate a payload of at least 20 KGs. The USV should be able to be transported by three to four people by hand on foot for short distances. The total targeted weight of the entire USV system should be under 70 KGs. The USV must also be small enough to fit on a standard-sized pickup truck bed.
- **Safety and reliability**: With the high cost of onboard equipment, safe execution of the bathymetric survey is paramount. Extensive testing must be conducted during the research phase to ensure fail-safe performance under extreme conditions, minimizing the risk of damage or loss. These requirements form the foundation for the USV’s design, ensuring robust performance in challenging survey environments.

Multibeam Echosounder Sensor

A MBES transmits a sound pulse with a specific frequency rate and sound frequencies, and it receives the same pulse return bounced back from a solid surface. It measures the time difference between transmitting pulse and receiving pulse and calculates the distance measurement using sound velocity. The MBES system has an integrated water velocity measurement sensor since water velocity changes with temperature. In addition, users may use an external sound, temperature sensor data logger, as shown in Figure 1.1, to measure the sound velocity and temperate at different depths. Some MBES systems have an integrated Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) system to accurately geolocate measurement points. The IMU is vital for keeping accurate position and orientation even with short GNSS signal outages. The selection criteria for MBES are:

- Cost, size, and weight.
- GNSS/IMU system performance and post-processing software capability.

- Measurement rate, sensor field of view (FOV), number of measurements within the FOV, sound beam angle size, and ability to change the FOV within configuration software.

Figure 1.1: Valeport SWiFT Sound Velocity Profiler data logger for measuring water sound velocity, water temperature, and pressure at different water depths

The IMU performance is proportional to cost. Higher cost IMU options enable more accurate data to be collected without GNSS signal under a bridge. The expected transit time under a typical bridge is about 30 seconds. Based on previous AHMCT research experience, good GNSS/IMU post-processing software in conjunction with local GNSS base station data can greatly improve vehicle position and orientation accuracy. The SMI project requires the collection of data on bridge columns up to the water surface. Previous operational experience with a MBES sensor with fixed FOV required an operator getting the boat or USV very close to the bridge columns, resulting in higher risk of collision with bridge columns or debris underwater. In a previous research project, the MBES sensor mounting system was designed to allow the MBES sensor to tilt up to 30 degrees to either side. Making the mounting angle change can be time consuming in the field and requires changing the sensor offset parameters into the software. Advanced MBES has a software configurable sensing FOV, which is a highly desirable feature for SMI operations.

Mechanical Requirements

USV Speed Estimation

Our survey is centered around rivers and their tributaries. To estimate the required speeds, it is essential to identify high-flow regions and assess river flow velocities. A simple estimation involves using volumetric flow rates from the California Data Exchange Center (CDEC) [2]. By dividing these flow rates by the river's cross-sectional area at a given location, we can obtain a rough estimate of the expected flow speed.

$$Volumetric\ Flow\ Rate\ (Q) = Velocity\ (V) * Area\ of\ Cross - section\ (A)$$

Say for example, the flow rate at a specific location—obtained from the CDEC—is 1,000 cubic feet per second (CFS). The river at this location has a depth of 10 feet and a width of 50 feet. Assuming a semi-elliptical cross-section, the cross-sectional area is calculated as:

$$Area\ of\ Cross - section\ (A) = \frac{1}{2} * Depth * \pi * \frac{Width}{2}$$

With the given values, the area of cross section is 392.699 sq. ft. With a flow rate of 1,000 CFS, this yields a speed of 2.55 ft/sec or 1.5 knots. Hence the USV must be able to accelerate and hold speeds faster than 1.5 knots to fight against these flow rates

Brief searches of various times of the year showed that high flow rates are commonly seen in the Sacramento River and other major California rivers, such as the American River at Chili Bar and North Fork Dam, where water velocities typically range from 3 to 5 knots. Considering these conditions, along with standard bathymetry survey speeds of 2 to 5 knots, a maximum operational speed of 7 knots (3.6 m/s) was selected for the USV.

Hull Selection

The hull of the USV serves as its structural framework, providing both stability and buoyancy. It is typically constructed from durable, lightweight materials such as carbon fiber, high density plastics, etc. Additionally, the hull houses and protects essential internal components, including computers for sensors, boat controllers, GPS, and batteries. Two parameters describe a hull: its profile/configuration and its form/shape.

The hull configuration/profile influences USV hydrodynamics, thereby playing a critical role in stability, speed, maneuverability, and resilience to diverse environmental conditions. Hull form/shape describes its interactions with water that then critically affect hydrodynamic drag. Hull selection primarily depends on its effectiveness in the maneuverability in tight spaces, reduced hydrodynamic drag, payload capacity, and cost.

There are two choices for the USV configurations: catamarans and monohulls as shown in Figure 1.2. A catamaran's twin-hull design provides better roll stability but can pose challenges in weight distribution due to the deck space being used for electronics. Monohulls, on the other hand, are easier to maneuver in tight spaces and often excel at upstream navigation thanks to their deep keel design [3]. Its superior maneuverability in tight spaces, for example near areas with vegetation or near bridges where personnel access is limited, is an important advantage. Additionally, the monohull's structure provides a simpler setup by allowing for easier integration and protection of all equipment inside the hull, reducing the need for extra wiring, and providing more flexibility in setting the center of gravity for stability purposes [3]. They are also typically less expensive in terms of fabrication and maintenance compared to catamarans. As such, a monohull seems to be the better choice for bathymetry operations.

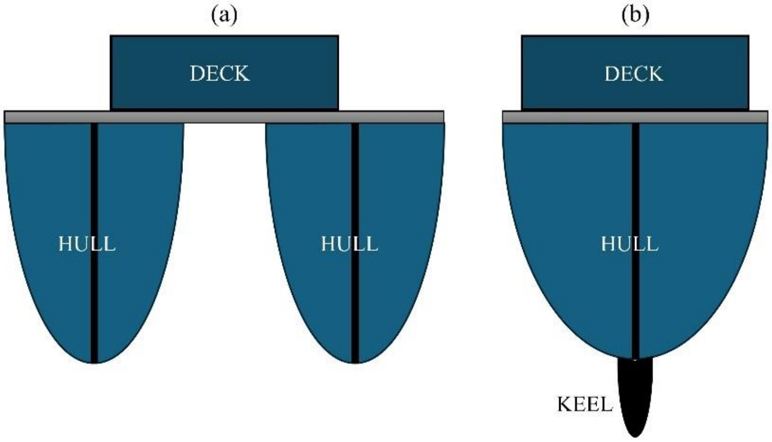

Figure 1.2: Catamaran and monohull

The hull shape also affects the stability, drag, and overall performance of a USV. Common hull shapes used for USVs include round, rectangular, V-shape, and stepped-bottom designs as shown in Figure 1.3. Choosing the appropriate hull shape depends on the specific requirements of the USV, including its intended use, operational environment, and performance goals. Each shape offers distinct advantages and trade-offs in terms of stability, drag, manufacturability, and overall efficiency. More about these hull shapes can be found in [4]. V-shaped and stepped hull designs are most commonly chosen for high-speed operations. The V-shaped hull was the most appropriate choice for our application as it offered an optimal balance of speed, stability, and performance.

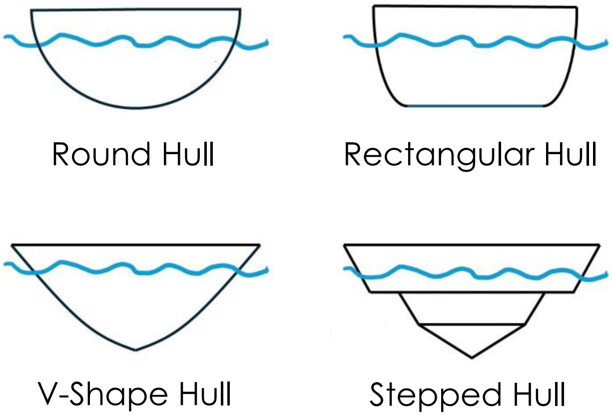
Round Hull
Rectangular Hull
V-Shape Hull
Stepped Hull

Figure 1.3: Common types of hull design

Estimation of Total Hull Resistance

To meet the maximum speed requirement, a thrust estimate is required, which in turn depends on the drag on the USV during operations. The drag on a USV can be represented as a sum of viscous drag (friction between the hull and the water), wave drag (drag due to wave generation as the hull moves through the water), and air resistance (drag due to air moving around the hull). Drag buildup is show in Figure1.4 and can be represented by an equation as:

$$R_{TOTAL} = R_{VISCOUS} + R_{WAVE} + R_{AIR}$$

The drag of a USV depends on several factors, including lateral speed, hull geometry—such as draft (D; the vertical distance from the waterline to the bottom of the hull), beam (B; the widest part of the vessel), wetted surface area (S_{wet}; the hull's contact area with water), and overall length (L). **The Viscous Drag**, $R_{VISCOUS}$ increases with speed as shown in Figure 1.4. It is caused by the friction and pressure forces on the hull due to the USV's motion. Based on the assumption of a flat plate geometry for the hull, corrected for form factor as outlined in [4], viscous drag can be approximated as:

$$R_{VISCOUS} = \frac{1}{2} * \rho * v^2 * C_F(1 + K) * S_{wet}$$

Where $\rho,\ v,\ C_F,\ K$ are the water density, velocity of the USV, coefficient of friction, form factors, respectively. The coefficient of friction can be calculated as:

$$C_F = \frac{0.075}{\left((\log_{10} R_n)\ -\ 2\right)^2}$$

R_n is the Reynolds number of the fluid. K is the form factor of the USV, which can be calculated as:

$$K \approx 19\left(\frac{\nabla}{D * L^2}\right)^2$$

∇ is the volume of the fluid displaced by the USV. S_{wet} can be calculated as:

$$S_{wet} = 2 * (L * B + B * D + L * D)$$

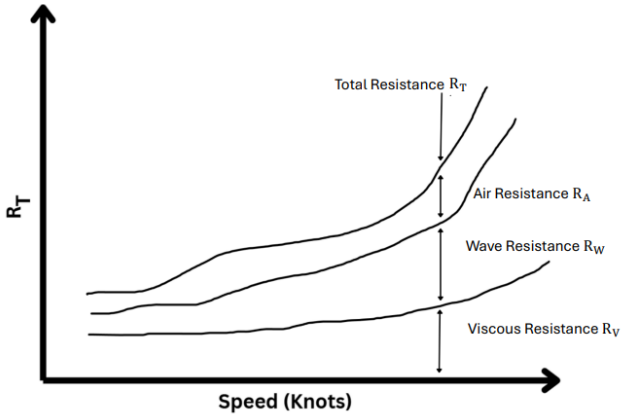

Figure 1.4: Drag components increase with increases in speed

The wave drag R_{WAVE} forms a significant portion of the total drag at higher velocities as seen in Figure 1.4. Naval architects use the dimensionless Froude number F_n, defined below, to predict the significance of wave drag:

$$F_n = \frac{v}{\sqrt{g * L}}$$

Where g is the acceleration due to gravity. When $F_n > 0.5$, the wave drag forms a significant part of the total drag. Estimating wave drag requires complex numerical and experimental studies, which were performed in [5]. Based on empirical data, the wave drag can be calculated as:

$$R_{WAVE} = \Delta * c * e^{m_1 * F_n^{-0.9} + m_2 * \cos(\lambda * F_n^{-2})}$$

Where Δ is the mass displacement of the USV. The model parameters c, m_1, m_2, and λ can be calculated as:

$$c = 569 * \left(\frac{B}{L}\right)^{2.984} * C_M^{-0.7439} * C_{WL}^{1.2655}$$

$$m_1 = -4.8507 * \left(\frac{B}{L}\right) - 8.1768 * C_P + 14.034 * C_P^2 - 7.0682 * C_p^3$$

$$m_2 = -0.4468 * e^{-0.1 * F_n^{-2}}$$

$$\lambda = 1.446 * C_P - 0.03 * \left(\frac{L}{B}\right)$$

Where, C_P and C_{WL} are the prismatic and waterline coefficient of the USV. Readers are encouraged to refer to [4] for further explanation and calculations.

Electronics Requirements

Power Source

For electric USVs, several power sources are available, including lithium polymer (LiPo), lithium-ion (Li-Ion), solid-state batteries, hydrogen fuel cells, supercapacitors, and solar panels. LiPo batteries are often preferred due to their lightweight design, high capacity, and superior energy density, making them ideal for applications where weight and power efficiency are critical. Li-Ion batteries offer longer cycle life and improved safety but are generally heavier. Solid-state batteries, an emerging technology, promise even higher energy density and enhanced safety. Hydrogen fuel cells provide extended endurance and quick refueling, making them suitable for long-duration missions. Supercapacitors are often used alongside batteries to deliver rapid bursts of power when needed. Solar panels can supplement battery power for endurance missions, particularly for long-range USVs and UAVs operating in open environments. Each power source has trade-offs in weight, energy density, lifespan, and operational efficiency, depending on the specific USV application.

The selection of a power source depends on several key factors, including endurance, weight, burst current output capacity, and cost. The power system must provide sufficient capacity to sustain at least one hour of continuous operation while remaining lightweight to minimize additional load on the USV. It should also be capable of delivering high burst currents when required, particularly during rapid accelerations or high-power maneuvers. Cost plays a crucial role in ensuring a balance between performance and affordability.

Control Modes

As discussed in the following sections, flight controllers (both hardware and firmware) are responsible for USV control, enabling both remote operation and autonomous missions. These controllers generally feature various control modes for flexible operation, such as manual control by a human operator or automated waypoint navigation.

Common control modes for a USV include manual and autonomous operation. In manual mode, the USV can be teleoperated via a ground control station using a remote control, joystick, or radio transmitter. This mode provides real-time control, making it ideal for precise maneuvering in confined waterways or obstacle-rich environments.

Alternatively, autonomous missions can be executed by programming waypoints in ground-station software. These missions rely on GNSS-based navigation to follow predefined routes, adjust speeds, and execute behaviors, like loitering or returning home, in case of communication loss. Autonomy can be further enhanced with onboard sensors for obstacle avoidance and adaptive path planning. In addition to these factors, common modes include return to home and loiter/hold, which are addressed in more depth in later chapters.

To ensure effective deployment, a balance between manual and autonomous operation should be evaluated through field trials. Additionally, an operational manual should be developed to guide surveyors on the advantages and limitations of each mode, helping them to choose the most suitable approach based on survey conditions. The availability of different control modes plays a crucial role in the selection of USV instrumentation and ground-station.

USV Instrumentation

Flight controllers, originally designed for UAVs, have been widely adapted for USVs due to their navigation and control capabilities. Popular choices include Cube Orange, Pixhawk, Navio2, and VectorNav, each offering unique advantages. For example, VectorNav provides a suite of products and firmware for high-precision navigation and control for uncrewed vehicles. ArduPilot and PX4 are community-driven and maintained open-source projects focusing on affordable solutions for uncrewed vehicles. In addition to flight controllers and firmware, additional components, such as GPS, rangefinders, proximity sensors, First Person View (FPV) goggles, are required to ensure safe and reliable bathymetry operations.

Selecting these components primarily depends on degree of accuracy and precision needed for bathymetry operations as well as cost, support of control modes, availability, and community support.

Ground Station and Telemetry

A ground station is typically used to steer the USV and monitor its telemetry and health. This station consists of hardware for controlling the USV and software running on a computer or tablet, which connects to the USV via radio at common frequencies, such as 915 MHz, 2.4 GHz, or 5 GHz. Higher frequencies provides higher bandwidth, which is preferred for live streaming camera feeds from the USV. Lower frequencies offer more robust communication around blockages caused by structures, such as bridge column. Figure 1.5 shows a pair of 915 MHz telemetry radios for USV application. The hardware includes a remote controller for manual operation, while the software interface receives and displays telemetry data and video feeds.

Figure 1.5: 915 MHz Radio System

Radio communications are generally limited to line of sight (LOS); although, signal repeaters can be deployed in the field to extend range and ensure reliable connectivity, particularly in challenging environments, such as around bridge columns where LOS may be obstructed. These repeaters enhance mission safety by maintaining consistent communication with the USV. Ground stations are available in two configurations:

- **Decoupled system** – This setup includes a separate remote controller for steering the USV and a computer connected via radio-link for telemetry and video feeds. This redundant system allows for independent control and monitoring, making it easier to manage telemetry while reducing the risk of data loss. However, it also requires additional power sources, equipment, and personnel to operate efficiently.

- **Integrated system** – In this configuration, an Android tablet or similar device displays telemetry data overlaid on video feeds, combining control and monitoring into a single unit. This setup reduces the number of operators required, simplifying deployment. However, it also increases the workload on the pilot, particularly in high-flow regions, and reduces redundancies, which could impact the safety of operations.

Each approach has its advantages, and the choice between decoupled and integrated ground stations depends on the mission requirements, team size, and environmental conditions. The selection criteria for ground stations include enhancing situational awareness for the pilot/helmsman, a user-friendly interface, ease of operator training, signal range and reliability, fail-safe modes, cost, and support of control modes.

Thrusters, Propellors, Speed Controllers

USVs utilize various types of thrusters and propellers depending on their mission requirements. Common types include fixed-pitch propellers, controllable-pitch propellers, waterjet thrusters, and azimuth thrusters. Fixed-pitch propellers are simple, efficient, and widely used for small USVs, while controllable-pitch propellers allow for variable thrust and improved maneuverability. Waterjet thrusters provide high-speed propulsion and are ideal for shallow waters, whereas azimuth thrusters offer 360-degree thrust vectoring, enhancing precise control for station-keeping and dynamic positioning. The choice of thruster or propeller depends on various factors, such as speed, efficiency, maneuverability, and environmental conditions.

Speed controllers regulate the power delivered to thrusters, enabling smooth acceleration, deceleration, and directional control in USVs. Electronic speed controllers (ESCs) are commonly used for electric thrusters, offering precise PWM-based or Controller Area Network (CAN)-based control. Variable frequency drives (VFDs) are employed in larger USVs with AC motors, allowing fine-tuned speed adjustments. Advanced field-oriented control (FOC) methods improve efficiency and response time, particularly for brushless motors. The right speed controller ensures efficient energy use, smooth operation, and improved longevity of propulsion systems. The selection of thrusters, propellors and speed controllers is driven by speed requirements, supporting power-sources available on-board, maintenance, maneuverability, and response/update time.

Chapter 2:
Development of a USV-based bathymetry system

Introduction

A thorough search was conducted to identify either a complete bathymetry-USV solution or identify and assemble commercial-of-the-shelf (COTS) components to build a bathymetry USV system. The following chapter discusses both these pathways and justifies the various components chosen for each subsystem along with the upgrades performed.

The collision mitigation system, including a Raspberry Pi, Blue Robotics Ping Sonar, and Slamtec S3 LiDAR, are discussed in the later chapters. This chapter focuses on the control, sensing aspects of the USV system.

MBES System

The Norbit iWBMSe MBES was selected as the bathymetric survey sensor. This MBES is a compact, high- resolution, broadband COTS system produced designed for bathymetric surveying. Aside from the survey requirements, the MBES selection was constrained by budget limitations. This MBES is equipped with an integrated GNSS-aided inertial navigation system and hence, can position and roll stabilization, enhancing accuracy. This sonar transducer operates at a center frequency of 400 kHz with a frequency range of 200 to 700 kHz and a ping rate of up to 60 Hz.

Other MBES systems from Norbit and other manufacturers were evaluated based on their published specifications. Better GNSS-aided inertial navigation system options are available, but the cost did not fit within the available budget. The SMI project requires collection of bridge columns up to the water surface. The chosen iWBMSe MBES has a software configurable sensing FOV feature that enables users to collect data on bridge columns up to the water surface. This feature is highly desirable for SMI operations. Figure 2.1 shows the Norbit iWBMSe system, which consists of two GNSS antennas, a MBES sensor, a compute unit, and cables inside a shipping and storage case.

Figure 2.1: Norbit iWBMSe system

Mechanical Components

Hull Selection

We evaluated several commercially available USVs, including the Phantom H-175 by Deep Ocean [6], Otter by Maritime Robotics [7], Catarob-ATS by Subsea Tech [8], EchoBoat-160 by Seafloor Systems [9], SONAR AMY by Hydronalix [10]. Based on the selection criteria discussed in Chapter 1, the Seafloor Systems EchoBoat-160 was chosen owing to its monohull configuration, which allows for better maneuverability and reduced drag. The EchoBoat-160 weighs 50 kg with a 27 kg payload capacity. It was estimated that final the USV configuration would not exceed the payload capacity. The EchoBoat-160 is equipped with two thrusters. AHMCT researchers upgraded thrusters for higher speeds after procurement. The hull dimensions are 1.7 m (L) × 0.8 m (B) × 0.24 m (H), which would fit inside a standard truck bed. The EchoBoat-160 was designed to have a MBES system integrated with minimal changes to the hull. Figure 2.2 shows an access hole in the middle of the EchoBoat-160 hull for mounting the MBES sensor. Figure 2.3 presents the Echoboat-160 USV along with other components discussed in the following sections.

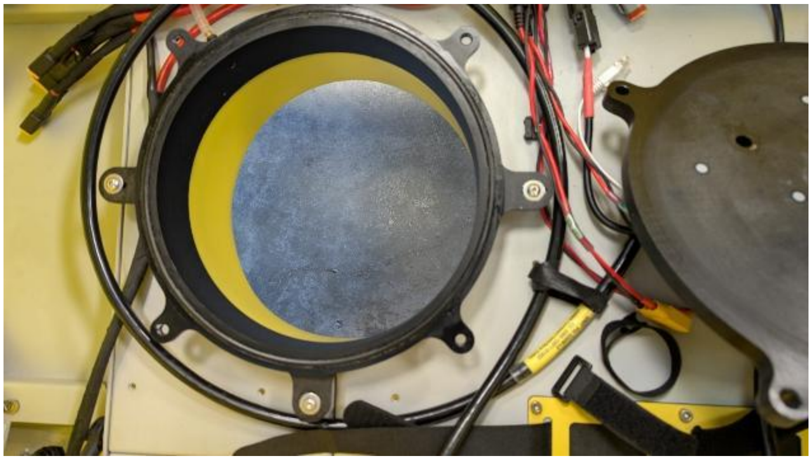

Figure 2.2: MBES sensor mounting and access hole in EchoBoat-160 hull

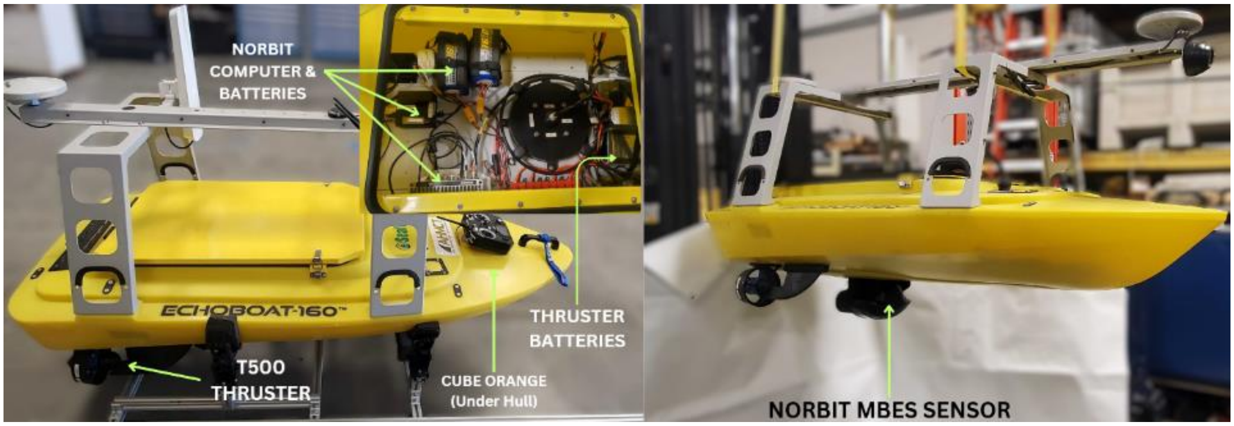

Figure 2.3: EchoBoat-160 with upgraded thrusters, controllers, and MBES Sensor

Electrical System

Power Source

LiPo batteries were selected as the power source due to their lightweight design, high capacity, and energy density. Their high discharge rate ensures rapid power delivery to the thrusters, which is essential for dynamic maneuvering. Based on the thruster power requirements and the desired minimum operation time of one hour, we chose three 6S, 28,000 mAh, 25C LiPo batteries, each weighing 6.72 pounds, from Tattu for powering the USV propulsion components. This configuration provides sufficient power for approximately over 5 hours of survey operations according to the pilot field test while also delivering high burst currents needed for maneuvering in high-flow conditions during flood operations. Two 6S, 16,000 mAh LiPo batteries, each weighing 4.15 pounds, were used to power the data logging computer and MBES system. Both batteries can sustain over 5 hours of continuous bathymetric survey operation for both the computer and MBES system.

Thrusters, Propellors and Speed Controllers

The EchoBoat-160 is equipped with thrusters from the manufacturer. In order to meet the targeted 7-knot top speed requirement, both thrusters were upgraded. The Blue Robotics T-500 thruster provides thrust up to 16.4 Kg-force according to the manufacturer's specifications. It was selected for our thruster upgrade. Figure 2.4 shows the sizes comparisons between the original thruster (shown with purple propeller) and the T-500 thruster (shown with blue propeller). The T-500 thruster motor controllers were also upgraded along with the Quicrun WP8BL150 G2 speed controllers. The WP8BL150 G2 is air-cooled and waterproof. The EchoBoat 160 power distribution and fuse system were upgraded, as shown in Figure 2.5, to handle the higher T-500 thruster power and current (60 Amp) requirements. In addition, all motor and battery power wires were replaced with larger wires to support the higher current requirements.

Figure 2.4: Size comparison between original EchoBoat-160 thruster (purple propeller blade) and the T-500 thruster (blue propeller blade)

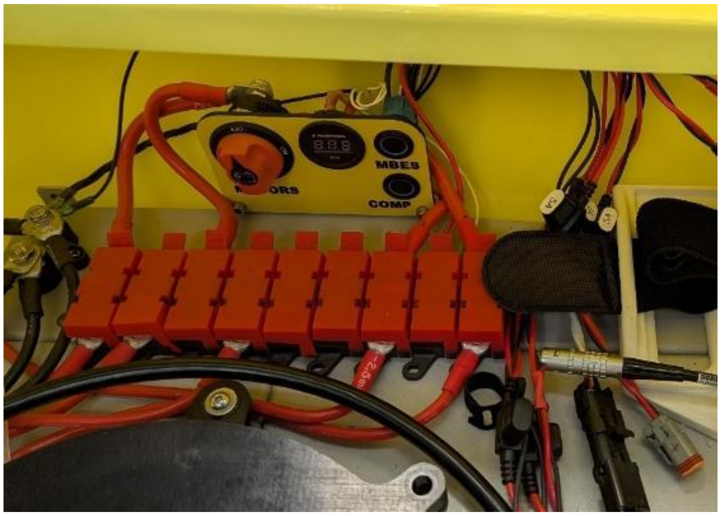

Figure 2.5: Upgraded electrical system control panel and fused power distribution for the EchoBoat-160

Table 2.1 presents the different drag components and the total estimated drag of the USV. While this table provides the expected drag, an additional safety factor of 1.5 was applied to account for sudden maneuvers and wind compensation. Furthermore, propeller efficiency in motion was considered to account for the thrust loss due to the USV's forward movement. As a result, the total estimated thrust required for the EchoBoat-160 to reach 7 knots is 538.07N. Given that each T-500 thruster produces a static thrust of 16.4 Kg-force at 24V, a total of four thrusters is needed.

Table 2.1: Estimated drag values

PARAMETER	VALUE
Viscous Drag $R_{VISCOUS}$	129.05 N
Wave Drag R_{WAVE}	86.18 N
Total Drag R_{TOTAL}	215.23 N

Instrumentation and Control

After reviewing various flight controllers and firmware options, the Pixhawk 6X board and the Cube Orange Plus, as shown in Figure 2.6, were selected. This decision was based on their high-quality onboard sensors, multiple redundant sensors and power inputs, compact form factor, and extensive open-source community support with continuous updates. Additionally, these boards offer multiple communication ports, enabling seamless integration of additional sensors, making it a robust choice for the USV's control system.

Figure 2.6: Cube Orange Plus (left) and the Pixhawk 6X board (right)

After extensive testing, the Pixhawk 6X was selected over the Cube Orange due to its additional serial communication ports, which enhance connectivity, and its metallic construction, which provides greater durability under repeated impact. The ArduPilot rover firmware was chosen for its seamless support and compatibility with a wide range of additional sensors, including range finders and companion computers for advanced processing. Additionally, ArduPilot natively supports community-tested obstacle avoidance algorithms, making it a superior choice for the USV's navigation and control system. The Here 4 Multiband GNSS receiver with built-in compass and IMU was selected for its high accuracy and position solution availability under challenging GNSS signal conditions, such as under bridges. The Here 4 GNSS utilizes CAN bus communication with Pixhawk 6X and Cube Orange, preserving serial ports for other sensors or data telemetry.

Ground Station

After testing both integrated and decoupled ground station configurations, a hybrid solution was selected. This approach allows the surveying team to decouple telemetry monitoring and control when needed, while seamlessly switching to an integrated mode when required. This flexibility is particularly beneficial for training new operators, enabling them to focus solely on USV control without distractions. More experienced operators can utilize the integrated mode, allowing for a more coordinated team effort focused on other aspects of the survey.

To aid this objective, we chose the SIYI MK32-HM30 Combo, a handheld ground station that integrates control and telemetry into a single Android tablet for the ground control set up. The system has a long transmission range of 15 kilometers, dual camera feed capability, and is compatible with signal repeaters (HM-30). The MK32 allows for telemetry streaming to an external computer via Wi-Fi or USB-C Cable. The processes are described in more detail in the operation manual for the USV. Since Pixhawk 6X allows for additional communication ports, a backup long range radio system (Figure 2.6) on the 915Mhz frequency was also set up to allow for a leaner communication system in cases where a high number of obstacles prevent effective communications or long-distance transmissions are required.

On the software side of the ground station, two popular options are Mission Planner and QGroundControl. QGroundControl is a better choice due to its cross-platform support, built-in video streaming support, and user-friendly interface.

Control Scheme

The Pixhawk 6X flight controller, running ArduPilot, offers multiple operational modes designed for varying levels of control, automation, and safety. These modes provide flexibility in USV operation, allowing for both manual and autonomous control, while incorporating critical fail-safe mechanisms. The following discussion explains these control modes in detail and their specific setup is explained in the user manual.

- **Manual Mode**: The helmsman directly controls the USV using a remote control (RC), with ArduPilot translating stick inputs into thruster commands. This mode provides full manual control, enabling precise maneuvering, heading adjustments, and speed changes. It is recommended to use manual mode to steer out of shallow regions and to reach the survey start location. This mode does not provide any kind of heading stabilization and therefore provides a greater freedom to the operator to control the USV aggressively. Unless the operator is experienced, it is advised to not use this mode during survey operations. This mode does not provide any obstacle-avoidance safety features.
- **Guided Mode**: This mode allows for real-time navigation commands from a ground control station to direct the USV to specific waypoints or targets. It is useful for quick adjustments during survey operations without predefined mission planning. This mode supports obstacle avoidance.
- **Loiter Mode**: The USV maintains its last known position and heading, actively countering external disturbances using the thrusters to stay within a 2-meter radius. This radius is configurable in real-time through the ground station, which is particularly useful in high-flow regions where station-keeping is required. This mode supports obstacle avoidance.
- **Auto Mode**: The USV follows a predefined mission plan, executing a set of waypoints programmed by the ground control station. This mode is ideal for surveying missions, ensuring systematic data collection with minimal operator intervention. This mode supports obstacle avoidance.
- **Acro Mode**: A highly responsive mode where the USV maintains its orientation unless changed by the operator, making it particularly useful for maintaining a steady heading during surveys. This mode helps novice operators keep the USV on a straight path, improving data collection

accuracy, especially in challenging flood conditions. However, Acro Mode requires a valid position estimate, and in cases where GPS or sensor drift occurs, unwanted twitching or instability may disrupt data collection. In such instances, it is advisable to switch to Manual Mode for direct control over the USV's movement. This mode supports obstacle avoidance.

- **Return to Launch (RTL) Mode** –When activated, the USV autonomously returns to its departure position, ensuring safe retrieval. This feature is also triggered as a fail-safe if low battery voltage, signal loss, or other critical issues are detected. It is essential to ensure that "Home" is a location on the water and not on land. This mode supports obstacle avoidance.

In addition to these modes, ArduPilot incorporates essential safety mechanisms, including arming checks to verify GNSS and compass availability before deployment and automatic RTL Mode activation in case of low battery or communication loss. These features enhance mission reliability and safety, ensuring uninterrupted survey operations even in challenging conditions.

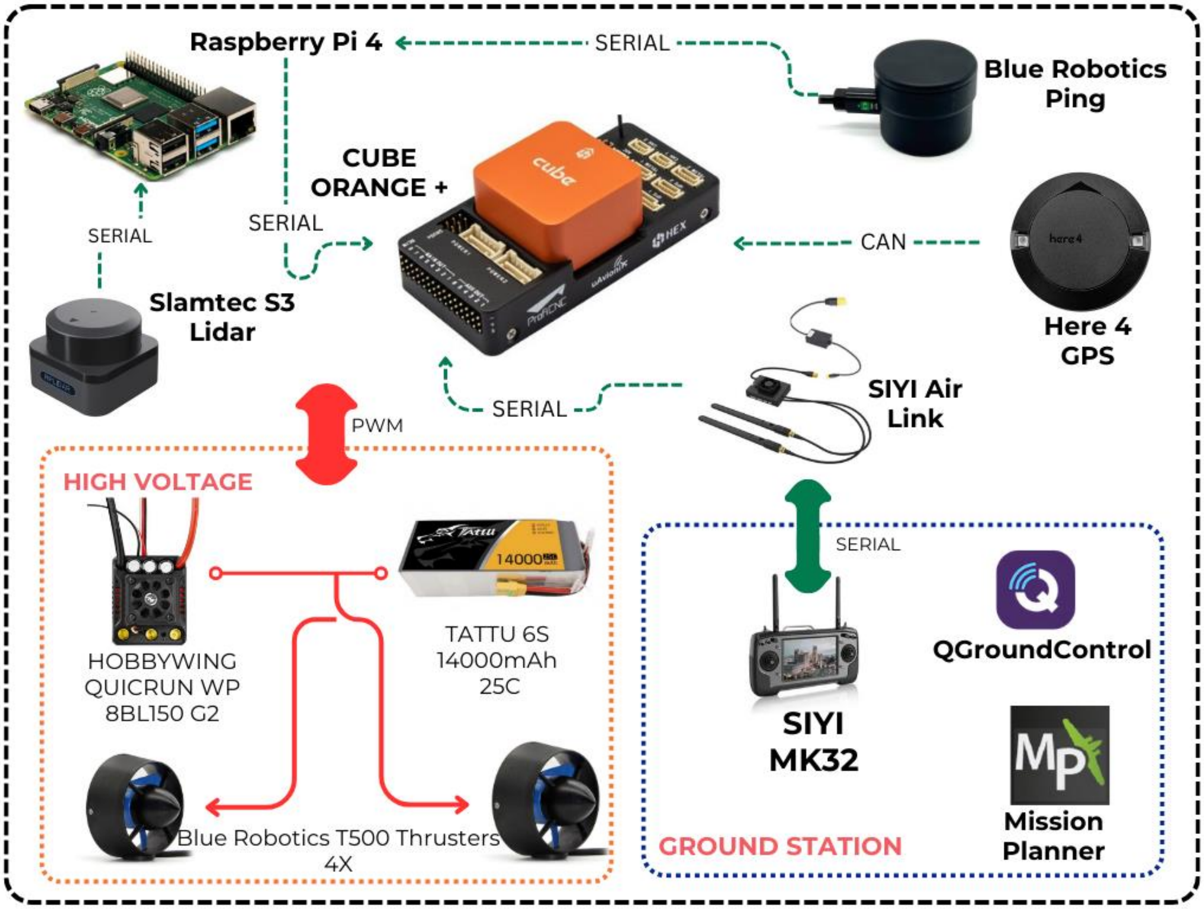

Figure 2.7: Complete Control System Architecture for the Bathymetry USV System

Chapter 3:
Testing the developed USV system

Introduction

The integrated bathymetry USV was tested under multiple conditions to evaluate its performance. Changes and upgrades were made based on the test results over a period of one and a half years. The USV was tested under calm conditions and high flow turbulent flood conditions. The following discussions outline the major tests and pilot projects conducted.

A custom cart, as shown in Figure 3.1, was designed and fabricated to reduce the USV deployment time at boat launches as well as provide a secure platform for transportation

Figure 3.1: EchoBoat-160 on a custom transportation cart being prepared for survey operations

Stonegate Lake in Davis, California

Several tests were conducted without the MBES system onboard at Stonegate Lake in Davis, California to evaluate the USV control system and familiarize operators with EchoBoat-160 operation. These tests helped to identify any area for potential improvement as well as ensure newly installed and upgraded components worked as expected and with reasonably good reliability. The test site was chosen due to its close location to AHMCT research center. Figure 3.2 shows both the EchoBoat-160 and research USV top speed testing at Stonegate Lake in Davis, California.

Figure 3.2: EchoBoat-160 and research USV testing at Stonegate Lake in Davis, California.EchoBoat-160

The top speed for EchoBoat-160 without the MBES system after the motor upgrade is about 2.3 m/s as shown in Figure 3.3. The EchoBoat-160 GPS speed (m/s) was plotted in Figure 3.3 from the data log created by ArduPilot rover software running onboard Cube Orange controller. Figure 3.3 also shows the USV trajectory. The green line represents USV under auto control following a path created by the user using Mission Planner software. The red line represents USV under manual control by operator.

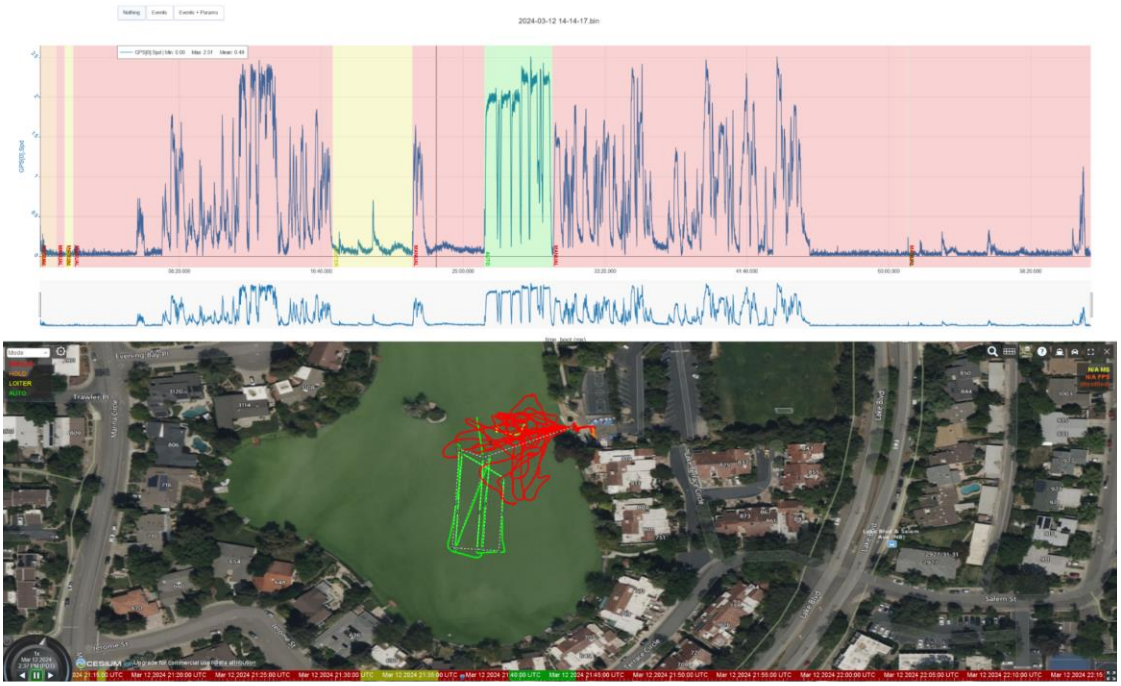

Figure 3.3: EchoBoat-160 top speed test result on 03/12/2024. The GPS speed (m/s) vs time chart is shown on top. The bottom image shows the EchoBoat-160 trajectory path. Image courtesy of Bing Map.

Lake Natoma Testing

EchoBoat-160 with the Norbit MBES system installed was tested at Lake Natoma a few times. Lake Natoma provided a large area with deep and calm water suitable for initial testing to gain operational experience in conducting bathymetric survey using the EchoBoat-160 USV. Caltrans SMI staff were present at the test to learn and practice how to deploy, control, and collect data using the USV system.

Figure 3.4: EchoBoat-160 testing at Lake Natoma, Sacramento, California

Pilot Projects Deployment

Caltrans SMI staff and AHMCT researchers worked together to deploy the USV bathymetric survey platform in several pilot projects at bridges in Northern California. The bathymetric data collected were post-processed and used for record purposes and data-driven decision-making processes. The following sections outline the pilot projects conducted during the research project duration. Each pilot project had its own challenges that pushed the limit of the USV platform's capabilities.

Sunrise Boulevard Bridge

The Sunrise Boulevard Bridge, over American river in Sacramento, California, is about a half mile from the boat launch dock. We performed runs to determine the USV top speed with MBES system and all batteries onboard. Figure 3.5 shows the USV speed vs. time and the USV trajectory. The maximum USV upstream GPS speed was 1.83 m/s, and the maximum USV downstream speed was 2.43 m/s. Therefore, the estimated top USV speed is about 2.1 m/s (6.9 ft/s). The maximum USV speed depends on USV's weight/draft and sensor protruding below water. The lower top speed is expected due to the added weight and drag of the MBES sensor.

Figure 3.5 shows three bridges. The larger bridge in the middle was the project site, and it was about a half mile west of the boat launch area shown in Figure 3.5 on the right. Some initial USV testing was conducted at the boat launch area to ensure all systems were functioning properly before proceeding to the project site. The project site presented several challenges.

The first challenge was the high river flow rate. The second challenge was the large changes in water flow current and turbulent water near the bridge column. These changes caused difficulties in controlling the USV, making it hard to have the boat follow straight paths for data collection. The USV struggled to travel up steam in some areas due to local high current flow. The third challenge was the high variation in water depth. The sand bank and shadow water area posed underwater collision hazards.

Figure 3.5: EchoBoat-160 testing at American River at Sunrise Blvd, Sacramento. Image courtesy of Bing Map.

Figure 3.6: EchoBoat-160 bathymetric survey platform pilot project at Sunrise Boulevard over American River in Sacramento

Emergency Project at Butte City Bridge

This operation was conducted over at the Butte City Bridge over the Sacramento River on February 15, 2025. The objective of this pilot project was to measure the riverbed depth around a bridge pier as shown in Figure 3.7. The challenges in this project included the lack of viable boat launch location. Boat launch ramp locations were far away from the project site, resulting in long journeys and depletion of batteries. The riverbank was rocky, muddy, full of vegetation, or had steep slopes; thus, it was impractical to launch the USV from the riverbank. The rapid water flow was not ideal for the Caltrans inflatable crewed boat. In addition, there was a lot of debris, both large and small, in the water. Finally, large changes in water flow current and turbulent water near the bridge pier caused difficulties in controlling the USV.

Figure 3.7: EchoBoat-160 Survey emergency pilot project in turbulent water at Butte City Bridge over Sacramento River. Image courtesy of Caltrans.

Working closely with Caltrans construction and the SMI crew, we developed a plan to launch the USV by attaching and lowering it from a personnel carrying basket using a crane as shown in Figure 3.8. A 100-foot long "safety" rope was attached to the USV to minimize risk of the USV floating down the river. The construction crew closed one lane on the bridge temporarily for the duration of data collection. To improve the USV performance, two of the propulsion batteries were not installed to reduce USV weight by 10 lbs. Since the estimated survey operation time was 2 hours or less, the reduction of battery power did not negatively impact the project. The "safety" rope limited the USV's area of movement, and it tangled with the GNSS antenna's support structure from time to time. We were able to untangle the rope by moving the USV and the rope. The riverbed depth data were compared to data collected using the Caltrans inflatable crewed boat with the Norbit MBES system in April 2023. Figure 3.9 shows both crewed boat and USV survey trajectory. Figure 3.10 shows the post-processed results.

Figure 3.8: USV attached to personnel carrying basket before lowering into Sacramento River using a crane. Image courtesy of Caltrans.

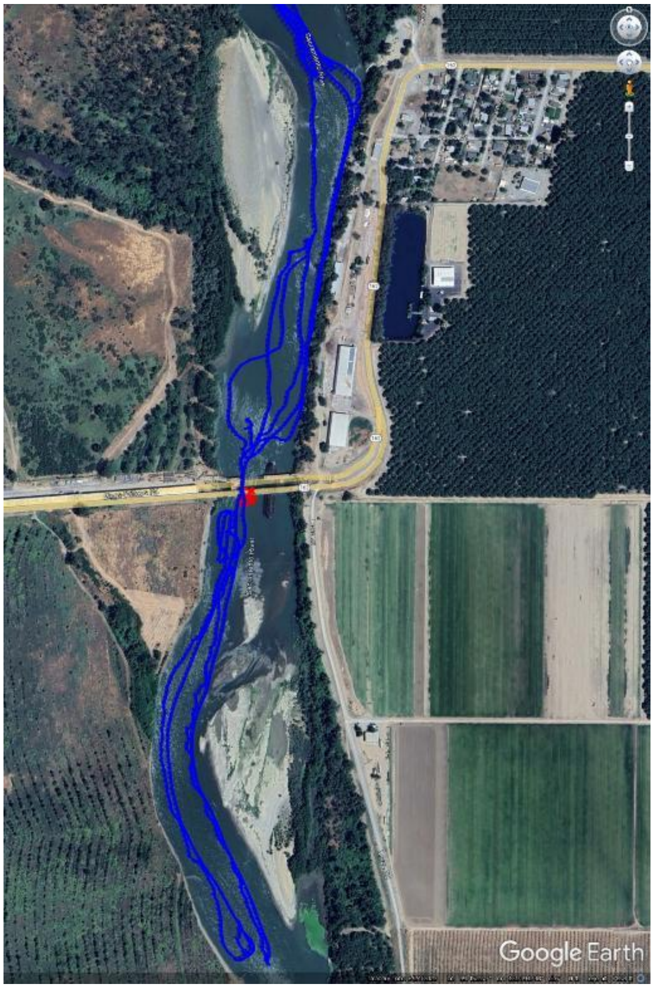

Figure 3.9: Inflatable crewed boat survey path (blue line) conducted on 04/05/2023 vs USV survey path (red) conducted on 02/15/2025 at Butte City Bridge over Sacramento River. Image courtesy of Google Earth.

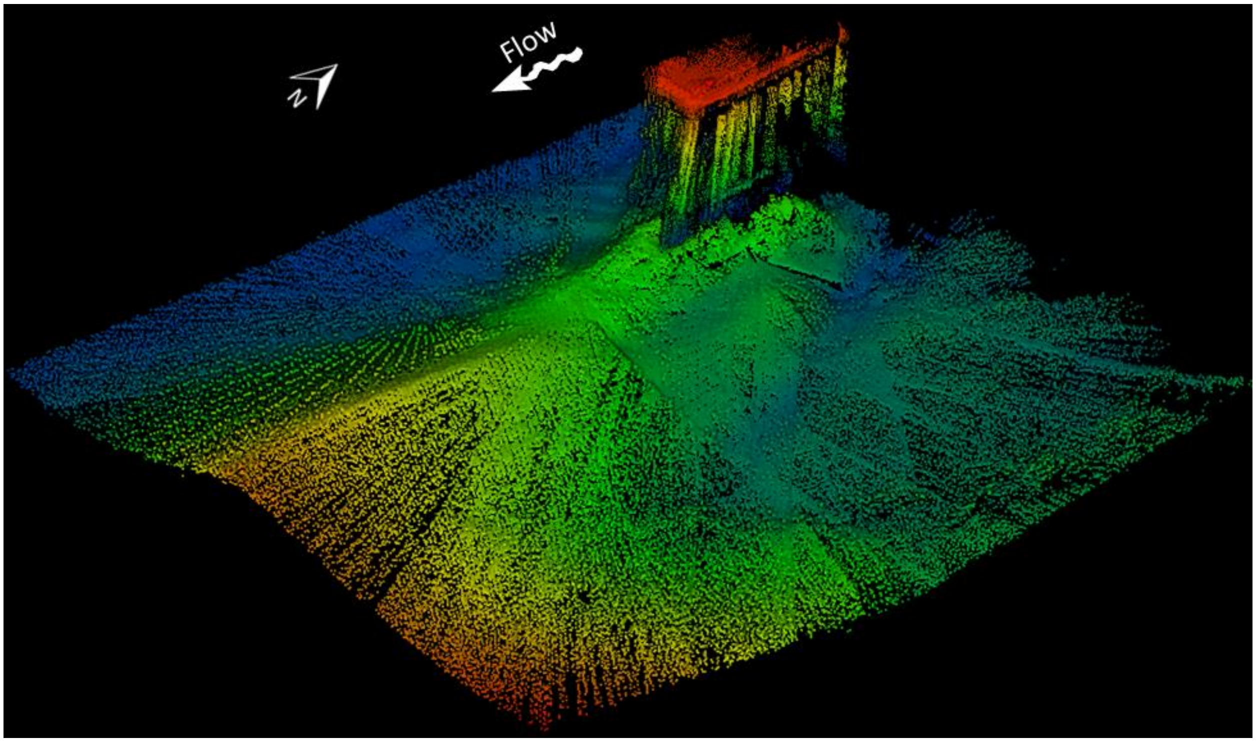

Figure 3.10: Butte City Bridge bathymetric survey results. Image courtesy of Caltrans.

Interstate Highway 5 Bridge over Calaveras

This operation was conducted under the Interstate Highway 5 over Calaveras River in Stockton, California. This pilot project objective was to collect bathymetric data upstream, downstream, and around the bridge pier at the Interstate5 bridge over Calaveras River near Stockton, California. Figure 3.12 shows the USV traveling toward under the bridge deck between piers. There were two challenges in this project. First, the boat launch ramp locations were far away from the project site, resulting in long journeys and depletion of batteries. The riverbanks were rocky, full of vegetation, and/or had steep slopes. Second, there were a few large pieces of debris floating down in the water.

Working with Caltrans SMI crew, we launched the USV from the riverbank where there was a narrow foot path opening. The USV was on the custom designed cart. Using the cart, SMI and AHMCY crew members rolled and slid the USV down the riverbank. The cart was attached to a vehicle winch, as shown in Figure 3.11, to control the speed of descent. The batteries (weighing 28 lbs) were installed after the USV was in the water to reduce its weight during the descent.

Figure 3.11: EchoBoat-160 launching from riverbank using custom cart attached to a vehicle winch line to control the descent into the water. Image courtesy of Caltrans.

Figure 3.12: EchoBoat-160 survey testing and training at Stockton

Figure 3.13 shows the USV survey trajectory. An AHMCT researcher conducted a training session for Caltrans SMI crew on post-processing the GNSS/IMU data using Applanix POSPac software using the pilot project data.

Figure 3.13: USV bathymetric survey path at a I-5 Bridge over Calaveras River at Stockton, California. Image courtesy of Google Earth.

Chapter 4:
Obstacle Avoidance System for USV

The successful, long-term operation of an autonomous USV depends on its safe handling and reliable navigation, which requires careful selection of sensors and the development of robust obstacle detection algorithms that then play a critical role in protecting both the USV and its surroundings.

This chapter outlines the processes followed for the selection and procurement of suitable sensors and how they were then integrated into the USV to enhance the vehicle's situational awareness and collision avoidance. Additional measures were placed to prevent system loss, minimize the risk of damage to nearby boats or infrastructure, and ensure the safety of people in the vicinity. By implementing fail-safe mechanisms, redundancy, and real-time obstacle detection, the USV can operate safely and effectively in dynamic environments.

Sensor Selection for Obstacle Avoidance

The sensor selection process was guided by these key criteria: outdoor and waterproof ratings, power consumption, weight, and compatibility with ArduPilot firmware. Given the diverse operational environments—both above and below water—multiple sensing modalities were required to ensure comprehensive coverage.

The following section details the selection process for above-water and underwater sensors. Both static and field tests were conducted to evaluate obstacle detection reliability, integration with ArduPilot firmware, and overall system performance. To mitigate the risk of damage to expensive equipment, a viable test platform—designed to replicate the hardware and firmware of the EchoBoat-160—was developed for extensive obstacle avoidance testing. This platform, referred to as the Research USV, enabled iterative testing and improvements before deploying the sensor on the EchoBoat-160.

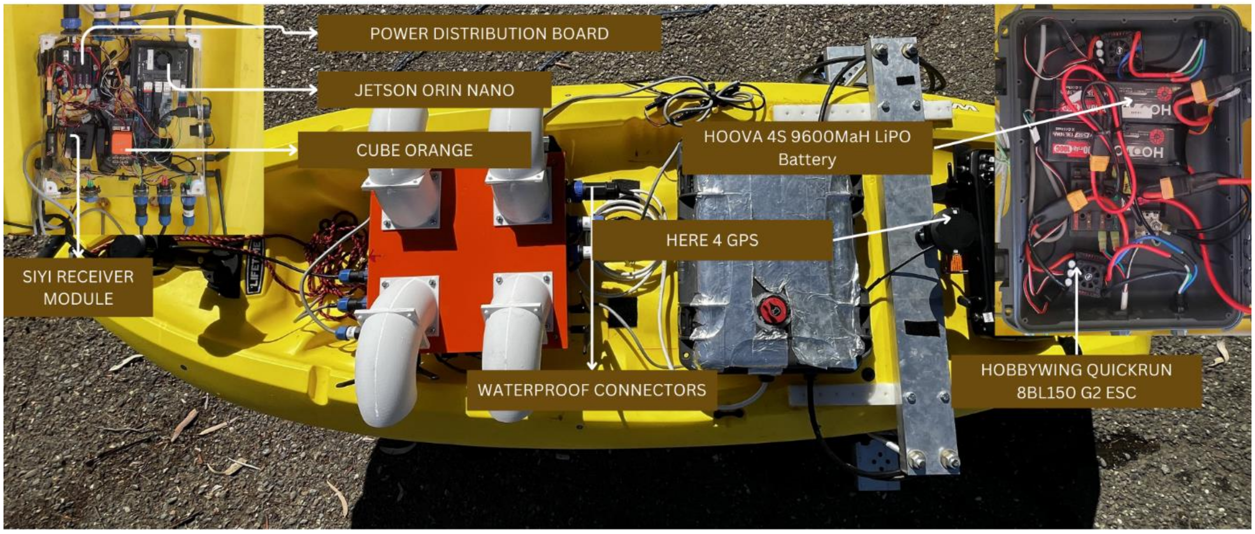

Figure 4.1: Research USV with all its electronics and control system

Above Water Sensor

Typical sensors used for above-water obstacle detection include cameras, radar, rangefinders, and LiDAR. Radar is effective for long-range detection and performs well in adverse weather but lacks the resolution needed for precise mapping in close-range applications. Rangefinders, while providing accurate distance measurements, are limited to a single direction, requiring multiple sensors to achieve full coverage around the boat. In contrast, 360-degree LiDAR enables comprehensive environmental mapping with a single sensor, offering superior coverage compared to radar and eliminating the need for multiple rangefinders.

For this project, the Slamtec S3 LiDAR, as shown in Figure 4.2, was selected for above-water obstacle detection. This 360-degree scanning LiDAR is specifically designed for outdoor environments and provides high-precision obstacle mapping.

Figure 4.2: Slamtec S3 LiDAR 360-degree LiDAR for above water obstacles detection

Underwater Sensor

For below-water obstacle detection, a variety of sensors can be used, including single-beam sonar, multibeam sonar, forward-looking sonar (FLS), and imaging sonar. Single-beam sonar provides depth measurements at a single point, making it useful for basic depth profiling but less effective for real-time obstacle avoidance. Multibeam sonar offers a wider FOV, mapping the seafloor or riverbed and submerged structures with high precision but at the cost of increased power consumption and data complexity. Forward-looking sonar (FLS), which projects sound waves in front of the USV, is particularly valuable for obstacle avoidance as it detects submerged hazards before the vessel encounters them. Imaging sonar, such as side-scan or synthetic aperture sonar, can provide highly detailed underwater imagery but is typically more suitable for surveying than real-time obstacle detection.

For this project, the Blue Robotics Ping 2 Sonar, as shown in Figure 4.3, was selected as the primary below-water obstacle detection sensor. This sonar module operates at 115 kHz, making it well-suited for detecting submerged obstacles while minimizing interference from water turbulence and suspended debris. Its narrow 25-degree beam width allows for focused measurements, improving detection accuracy in complex environments. It is also natively supported by ArduPilot and can be controlled via APIs for additional functionality.

Figure 4.3: Blue Robotics Ping 2 Sonar for underwater obstacles detection

Integration with ArduPilot

The ArduPilot cannot natively process both LiDAR and sonar data simultaneously, hence a single board computer (SBC), Raspberry Pi 4, is used for sensor fusion. The Raspberry Pi 4 processes data from both sensors, interprets obstacle information, and transmits the refined data to ArduPilot for navigation, enabling a robust, multi-sensor obstacle detection system capable of operating in complex marine environments.

Additionally, this setup allows for further data processing to enhance safety features, such as providing obstacle distance warnings to the ground control station via aural alerts and implementing emergency braking mechanisms. These capabilities are currently undergoing evaluation and refinement to ensure optimal performance in real-world conditions. Figure 2.2 depicts the full integration of these sensors with the ArduPilot system.

Obstacle Detection

Effective obstacle avoidance requires not only the selection of suitable sensors but also a precise understanding of their operation, data processing methods, and integration challenges. Following sensor selection, extensive static and field tests were conducted to evaluate mechanical configurations and optimize software-based filtering techniques for improved obstacle detection and environmental awareness.

Above-Water Obstacle Detection

The Slamtec S3 LiDAR serves as the primary above-water obstacle detection sensor, offering 360-degree scanning. Since the S3 LiDAR is not natively supported by ArduPilot, an external onboard computer was integrated to down sample the high-density LiDAR data before feeding it into ArduPilot. Unlike sonar, which requires extensive filtering, LiDAR processing is more straightforward, primarily focusing on efficient data reduction while preserving critical obstacle information.

LiDAR generates thousands of data points per revolution, making effective down sampling essential for real-time processing. After evaluating multiple approaches, three algorithms were shortlisted. The 360-degree space around the USV was divided into 72 sectors, each spanning 5 degrees. Within each sector, the following down-sample algorithms were implemented:

- Simple measurement at every 5-degree interval.
- Inverse distance weighing around the center angle of a sector.
- Inverse distance weighting around the lowest distance in a sector.

The third approach proved to be the most effective, preserving critical obstacle details while significantly reducing computational load. During implementation, special attention was given to memory management, ensuring the system remained stable and avoided memory overflows or crashes during long field operations. Additionally, buffering and memory management were optimized to ensure real-time data transmission for reliable obstacle detection and navigation above water.

Underwater Obstacle Detection

The Ping 2 Sonar was extensively tested in a controlled pool environment under varying mounting angles to determine optimal configurations for detecting both submerged obstacles and the seafloor. Through these tests, an angle between 10° and 20° was found to be ideal for forward obstacle detection, while higher angles were better suited for floor mapping. Based on these results, the sonar's final mounting position on the Echoboat-160 was determined.

To improve sonar data accuracy and reliability, various signal filtering techniques were explored, including:

- **Butterworth filter**: This is a low-pass filter smoothing the data, thereby eliminating any sudden changes to the sonar data. Tuning this filter is essential, and delay in sensor readings is inevitable.
- **Moving Average filter**: A 3-point or 5-point moving average is another viable option to help smooth the data, with the lag time being lower than Butterworth filters.

To assess the effects of turbulence and ensure reliable obstacle detection in dynamic conditions, initial tests were conducted in a static tub bench. The objective was to tune the confidence levels of the sonar sensor and evaluate the impact of turbulent water flow on detection accuracy. These tests provided valuable insights into the optimal mounting location and the influence of hull interference on sonar readings.

Field tests were then performed on the research USV where the sensor's location and height relative to the hull were frequently adjusted using custom mounts. To further evaluate the sensor's limitations under real-world conditions, the USV was tested at Davis Lake. During operations, the Raspberry Pi collected distance measurements, confidence levels, and GPS data, while systematically varying parameters, such as speed, mounting location, and sensor height. This iterative process helped identify sonar limitations and refine filtering techniques to improve data reliability. Based on these findings, the sonar sensor was mounted at a 12.5-degree angle below the waterplane, and a 3-point average filter was implemented to smooth out noise. Additionally, algorithms were developed and rigorously tested to prevent memory leaks or crashes, ensuring stable performance during extended field operations.

Sensor and ArduPilot Integration

With the sensor configurations finalized, ongoing work focuses on refining the data fusion algorithms to ensure seamless integration between sonar and LiDAR. The onboard companion computer Raspberry Pi manages preprocessing, filtering, and data transmission, enabling ArduPilot to make informed navigation decisions based on a multi-sensor perception framework.

Experimental Evaluation of Obstacle Avoidance

With the obstacle avoidance system fully developed and integrated, the next critical step is field testing to evaluate its real-world performance and compatibility with ArduPilot's native obstacle avoidance algorithms. This phase focuses on assessing the system's ability to detect and track obstacles, its reliability in maintaining consistent obstacle awareness, and ArduPilot's response time and behavior in various avoidance scenarios. Specifically, testing will analyze how ArduPilot's built-in path-planning methods handle dynamic and static obstacles, ensuring the system can effectively navigate and avoid in real-time, under operational conditions.

Natively ArduPilot includes three native obstacle avoidance algorithms:

- **Simple Object Avoidance**: This algorithm modifies control inputs to maintain a safe distance from detected obstacles or brings the USV to a halt if necessary.
- **BendyRuler Path Planning**: This algorithm dynamically recalculates the USV's path around obstacles and virtual fences using a real-time re-routing strategy.

- **Dijkstra's Path Planning**: This algorithm implements graph-based pathfinding to navigate around obstacles and virtual fences, ensuring an optimized route.

These algorithms operate by continuously analyzing distance data from onboard sensors, including LiDAR, stereo depth cameras, and sonar, to effectively detect and avoid submerged, floating, and overhead obstacles, enhancing safe and autonomous navigation.

After extensive field testing with the USV, Simple Obstacle Avoidance was selected as the preferred method for bathymetry operations. Field analyses during high-flow conditions highlighted unpredictability and rapid changes in the environment. Other obstacle avoidance algorithms, which attempt to reroute the USV around obstacles, were found to introduce unwanted trajectory deviations, potentially compromising stability and data accuracy.

Simple Obstacle Avoidance was chosen as the safest approach as it prevents unnecessary trajectory shifts by slowing down or stopping the USV when approaching an obstacle. This approach ensures that bathymetry data remains accurate, avoiding unwanted heading or track changes. Once an obstacle is detected, the USV will halt, requiring the operator to manually assess and carefully navigate around the obstacle before resuming the mission.

The control modes outlined in previous chapters behave as follows when obstacle avoidance is enabled:

- **Acro Mode:** The USV, while still being commanded by the operator, will slow down or stop upon close proximity to a forward-obstacle. Unless the operator navigates around the obstacle, the USV will not respond to forward commands, even with full throttle command. This mode is particularly useful when navigating under piers or shallow banks during surveying.
- **Auto Mode**: The USV, upon receiving a set of waypoints from the ground station, will navigate to those waypoints in succession. Upon seeing a potential obstacle, the USV will simply stop at its location and wait for the obstacle to move away. In case the USV seems to be stuck and unable to continue its mission, the operator can shift into Manual Mode and navigate around the obstacle before resuming the mission.
- **Loiter Mode**: This mode attempts to hold the position of the USV at the location where this mode was enabled. When an obstacle approaches the USV, it attempts to move away from the obstacle and maintain position at its new location. It is strongly advised that this mode is enabled when the operator has a good view of the USV and is certain no major obstacles are in its proximity.

- **Guided and Return to Home Modes**: Under both these modes, the USV will attempt to reach its desired destination, but upon detecting an obstacle will stop and maintain position until manual takeover or the obstacle leaves the USV's proximity.

These modes depend on multiple parameters, such as the avoid margin and acceleration rates, which dictate the algorithm's behavior. A critical goal of field tests is to determine and tune these parameters.

Chapter 5:
Enhancing the Crewed boat surveying platform

The Norbit MBES system can be used to improve the performance of the existing crewed boat-based sensing platforms (inflatable boat and dive boat) currently used at Caltrans for bathymetric surveying tasks. There are situations where the crewed boat platforms are a more appropriate choice over USV. For example, the dive boat can operate in the Northern California Bay water. The higher waves in the San Francisco Bay may flip a small USV. There are larger USV's that can operate in Bay water; however, they are not suitable for narrow and shallow river water ways. The inflatable crewed boat can operate for longer distances and durations.

Goals

The goal was to integrate the Norbit MBES system on to the inflatable boat and dive boat platforms for bathymetric surveying tasks. In addition, AHMCT researchers trained Caltrans SMI personnel in how to install and operate the integrated platforms in the field.

Inflatable Crewed Boat Setup

The improvements made to the existing Inflatable boat surveying setup were:

- Adapt the AHMCT-developed MEBS sensor platform from a previous project [1]to the new Norbit MBES system.
- Add larger capacity batteries to support longer surveying operations.
- Upgrade rugged field computers to better handle larger and faster data acquisition from the Norbit system.
- Document the modifications made and the best practices in using the upgraded inflatable boat bathymetric survey system.

Sensor Platform Setup

In a previous research project [1], AHMCT researchers designed and fabricated bathymetric survey platform for MBES system. New sensor brackets and GNSS antenna mount were developed and adapted the Norbit system to the existing survey platform as shown in Figure 5.1. The platform secures the rugged laptop, Norbit sensor computer, batteries, cables, and the GNSS antennas and MBES sensor assembly. The platform allows the GNSS antennas and MBES sensor assembly to rotate out of the water, as shown in Figure 5.1, for transit in water as well as launching and recovering the inflatable boat at boat ramps. Figure 5.2 shows the GNSS antennas and MBES sensor assembly flipped down with the MBES sensor below water when conducting data collection during a bathymetric survey. The inflatable boat and the survey platform are assembled in the field. They are later disassembled for easy transport.

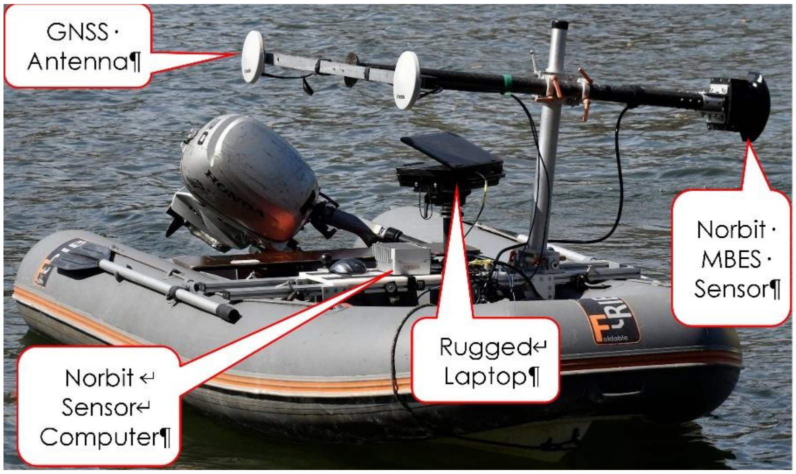

Figure 5.1: Inflatable crewed boat survey platform for the Norbit system

Figure 5.2: GNSS antennas and MBES sensor assembly flipped down with the MBES sensor below water

Computer aided design (CAD) models were created to ensure the entire platform assembly would fit together as well as keep an accurate record for future modification and fabrication. Figure 5.3 shows the CAD model of the GNSS antennas and MBES sensor assembly. Figure 5.4 shows a CAD drawing of the GNSS antennas and MBES sensor assembly. The CAD model in Figure 5.4 also shows a LiDAR sensor mounted on antenna bar. The CAD design has provision for mounting a LiDAR sensor for the future. The dimensions in the CAD drawing provide accurate, essential sensor offset information for BeamworX and Norbit GUI, bathymetric survey software, and sensor configuration inputs.

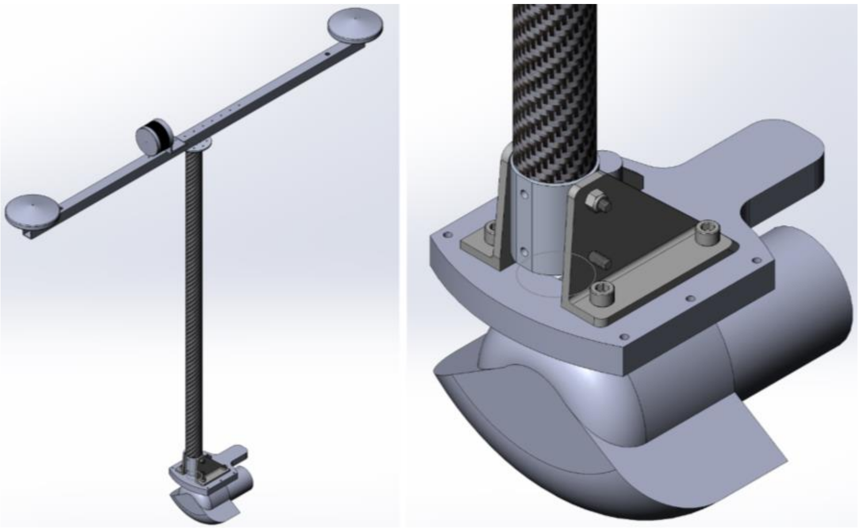

Figure 5.3: CAD model of the Norbit sensor mount

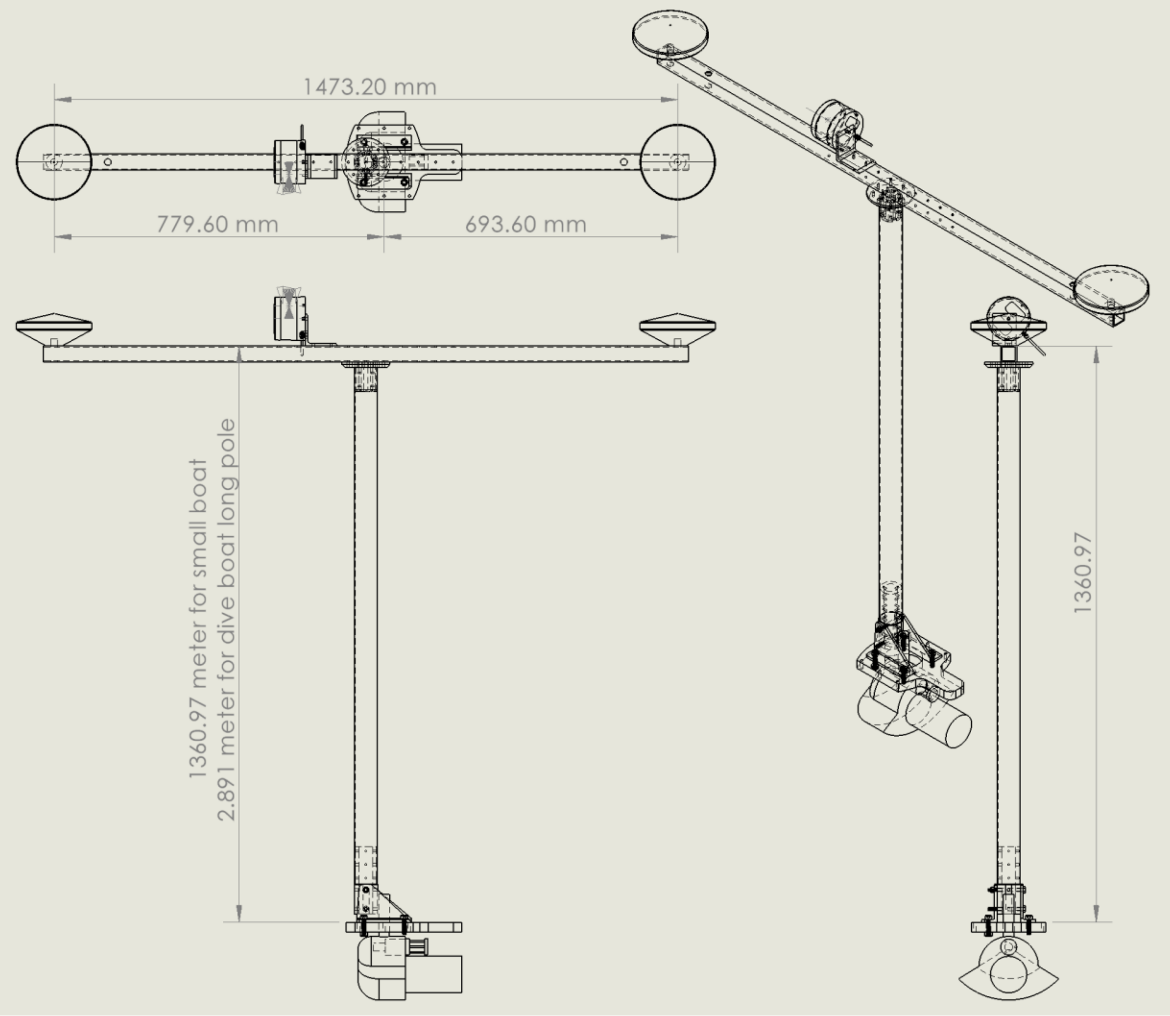

Figure 5.4: Norbit sensor mount CAD drawing with sensor offset measurements for bathymetric survey software configuration setup

Bathymetric Survey Using Caltrans' Inflatable Boat Platform

Caltrans SMI personnel and AHMCT researchers conducted pilot projects using the inflatable boat survey platform. The SMI crew members were trained to assemble the survey platform with the inflatable boat. We experimented with different sensor configurations to determine optimal setup for different scenarios using the Norbit system. AHMCT researchers provide technical phone support as well as repair for broken parts. Broken parts are primarily caused by collision with hard objects above or under water. A certain part of mounting platform was designed to break away first, thereby mitigating damage on vital and expensive components.

As a result, the SMI personnel have conducted bathymetric survey projects without AHMCT researchers. Figures 5.5, 5.6, and 5.7 provide examples of the inflatable boat survey path, shown in red lines, in projects conducted by SMI personnel.

Figure 5.5: Caltrans inflatable boat survey path on Sacramento River near I-80 highway at Sacramento. Image courtesy of Google Earth.

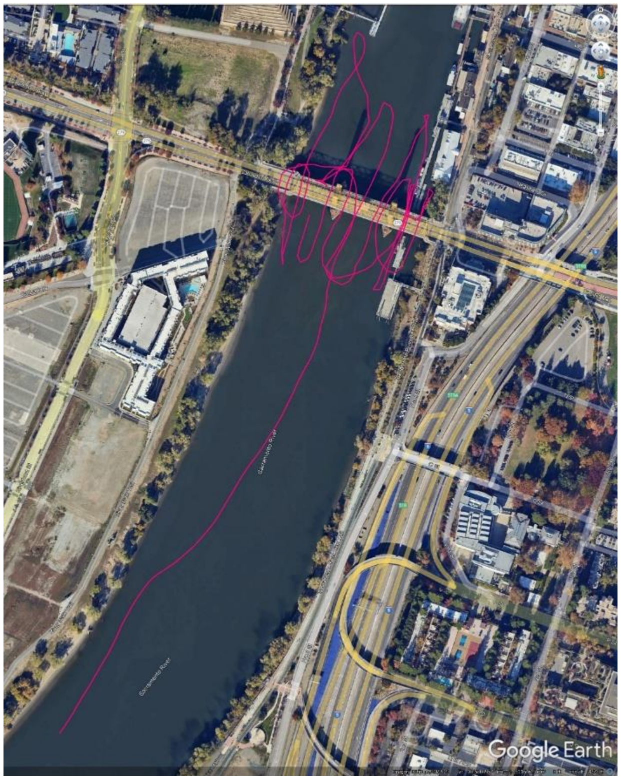

Figure 5.6: Caltrans inflatable boat survey path on Sacramento River near the Tower Bridge in Sacramento. Image courtesy of Google Earth.

Figure 5.7: Caltrans inflatable boat survey path on Sacramento River near interstate highway 5 at Sacramento Airport. Image courtesy of Google Earth.

Dive Boat Setup

Caltrans owns a dive boat, as shown in Figure 5.8, that supports diver inspection activities. Neither the inflatable boat nor the current USV is suitable to operate in the San Francisco Bay water. In a previous research project, AHMCT researchers designed and fabricated an MBES system sensor mount, as shown in Figure 5.9, for the Caltrans dive boat to support bathymetric surveys. The mounting system consists of a pole mounting assembly that clamps on to the side rail of the dive boat as well as a carbon fiber 9-foot-long pole, as shown in Figure 5.10, to which the MBES sensor and GNSS antenna bar are mounted on both ends. The MBES sensor bracket and GNSS antenna bar are from the inflatable boat survey platform. Like the inflatable boat survey platform design, the GNSS antennas and MBES sensor assembly can be flipped out of the water, as shown in Figure 5.9, for transit in water as well as launching and recovering the boat at boat ramps. The dive boat MBES sensor mount and sensors are assembled in the field, making them easier to transport.

Figure 5.8: Caltrans dive boat

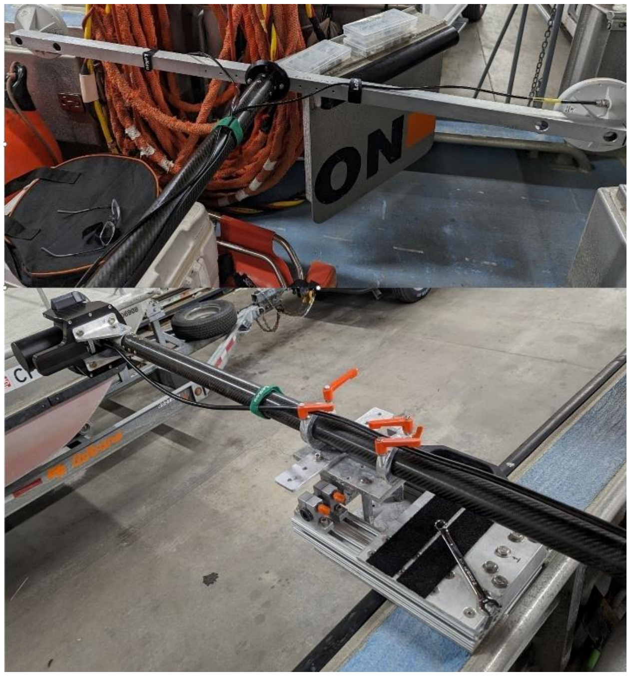

Figure 5.9: Caltrans dive boat MBES sensor mount

Figure 5.10: Caltrans dive boat MBES sensor mounting pole

The SMI crew members were trained to assemble the dive boat survey platform in the dive boat storage location as shown in the background in Figure 5.9. SMI personnel and the Caltrans dive boat crew have conducted bathymetric survey projects without AHMCT researchers at the Bay Bridge West Span. Figure 5.11 shows the dive boat survey path (red lines).

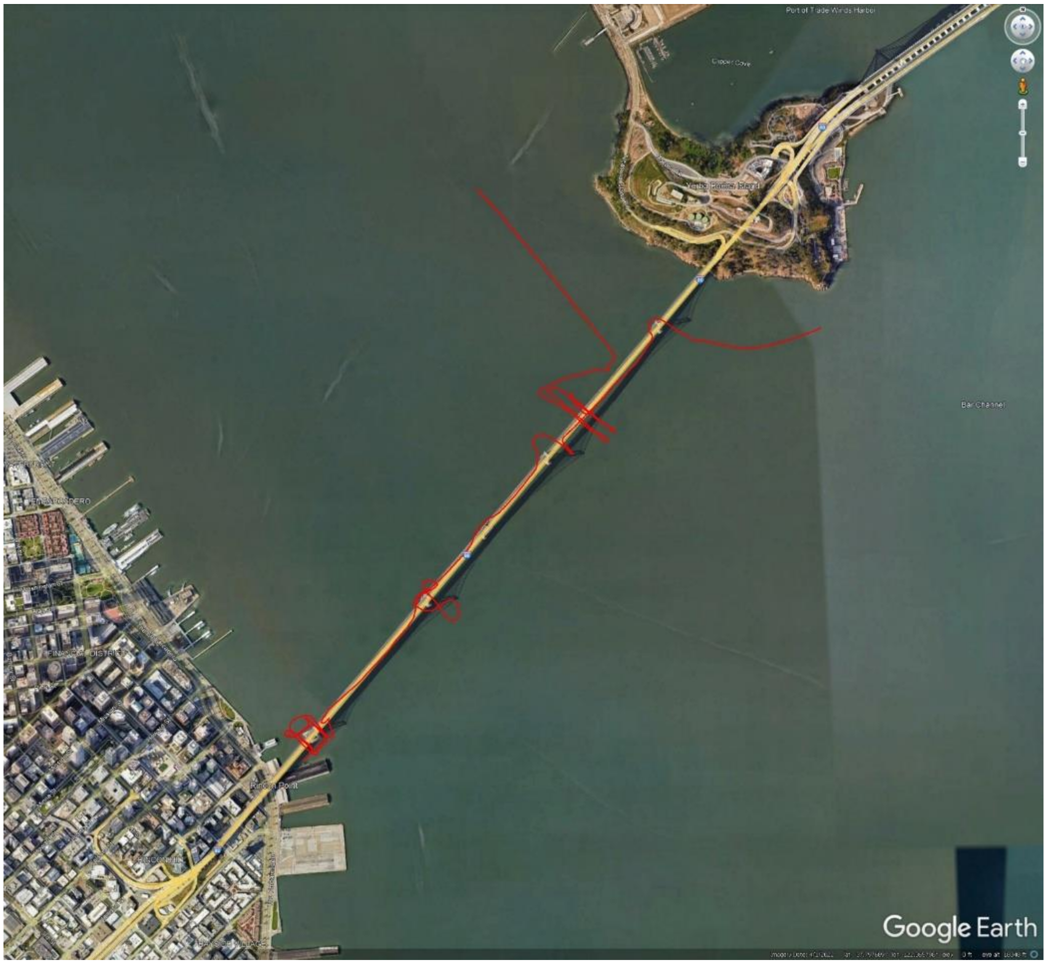

Figure 5.11: Caltrans dive boat survey path at the Bay Bridge West Span. Image courtesy of Google Earth.

Lessons Learned From Crewed Operations

SMI personnel have successfully conducted bathymetric survey projects using the Norbit system on both the inflatable boat and dive boat. Minor improvement can reduce the weight of the parts and improve the ease of assembly process. Spare parts are needed in case of damage in the field.

Chapter 6:
USV Deployment and Implementation Issues

Considerations for Reaching Full Product Deployment

Equipment Issues

The thruster motor controller required resetting during a few field tests, likely due to momentary overheating. The loss of one thruster would result in loss of steering. To mitigate this issue, components will be added to allow the operator to reset the motor controller using the USV remote control. The USV needs a temperature recording system inside the USV hull to monitor computers, motor controllers, and onboard electronics temperature.

Furthermore, debris can damage the motor blade, resulting in loss of steering or propulsion. Redundant steering and propulsion systems using additional motors, rutter, and/or a steerable motor mount would improve USV reliability.

A higher accuracy integrated IMU would improve data accuracy under bridges. However, survey grade IMU can be prohibitively expensive.

Operational Issues

Launching USV into the water can be challenging depending on the survey site location. Recreational boat launch sites can be far away from a project site. Deploying the USV from a riverbank can be hindered by steep terrain, thick vegetation, muddy and slippery slopes, or rocky embankments.

Debris in the water can damage thruster components. Extra spare parts are needed for repair. Operators should be prepared to cover part replacement and repair costs.

Chapter 7:
Conclusions and Future Research

Conclusions

Key contributions of this research project included:

- A field tested USV bathymetric survey platform with over 5 hours operating duration and a top speed of about 2.1 m/s (6.9 ft/s).
- Enhanced Caltrans crewed boats with bathymetric survey capability.
- Successful bathymetric survey pilot projects using USV, an inflatable crewed boat, and a crewed dive boat.

This project also explored multiple proximity sensors and avoidance algorithms to develop and test a simultaneous under- and above-water obstacle avoidance system. When an obstacle is detected in its vicinity, the USV halts in Auto, Guided, or Acro mode. Depending on the scenario, operator intervention may be required to navigate around the obstacle.

The Norbit MBES software configurable FOV feature has proven valuable in gathering data of bridge piers up to the water surface in pilot projects. It is an essential feature for any bridge site bathymetric survey system.

Future works

The obstacle avoidance system can be enhanced with additional sensing modalities, such as a stereo camera utilizing machine learning (ML) algorithms to detect obstacles ahead. This data can be fused with the existing system, addressing LiDAR blind spots. To further improve underwater obstacle detection reliability, additional sonar sensors—such as side-scan sonar or 360-degree sonar—can be integrated into the system. The MBES sensor data can also be incorporated to enhance detection capabilities, enabling operations in extremely shallow waters (>1 foot depth). Additionally, the avoidance algorithm can be improved by integrating reinforcement learning (RL) agents, allowing the USV to actively avoid obstacles with minimal disruption to data collection.

The USV weight may be further reduced to enhance its mobility performance. The number of batteries on board may be reduced depending on the expected operation time of a project. However, users may balance the benefits of lower weight at the expense of lower operational time.

The current T500 thruster propeller blade design is optimized for maximum thrust at low speed. Other T500 thruster users have experimented with different propeller blade designs to increase USV top speed. Using blades optimized for high-speed operation would improve the USV's efficiency and top speed without adding weight of additional thrusters.

The USV transportation cart should be modified to better traverse rough and steep terrain on riverbanks.

The thruster motor controller required resetting during a few field tests, likely due to momentary overheating. The loss of one thruster would result in loss of steering. To mitigate this issue, components should be added to allow the operator to reset the motor controller using the USV remote control. The USV needs a temperature recording system inside the USV hull to monitor computers, motor controllers, and onboard electronics temperature.

Furthermore, debris can damage the motor blade, resulting in loss of steering or propulsion. Redundant steering and propulsion systems using additional motors, rutter, and/or steerable motor mount would improve USV reliability.

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